Grass Hedge Effects on Gully Hydraulics and Erosion

S.M. Dabney[1], USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi
sdabney@ars.usda.gov, FAX 662.232.2988

F.D. Shields, Jr., USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi
dshields@ars.usda.gov, FAX 662.232.2988

E.J. Langendoen, USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi
elangendoen@ars.usda.gov, FAX 662.281.5706

D.M. Temple, USDA-ARS Hydraulic Engineering Research Unit, Stillwater, Oklahoma
dtemple@pswcrl.ars.usda.gov, FAX 405-624-4136

ABSTRACT. Concentrated flow can cause gully formation on sloping lands and in riparian zones adjacent to incising stream channels. Current practice for riparian gully control involves blocking the gully with a structure comprised of an earthen embankment and a metal or plastic pipe. Measures involving native vegetation would be more attractive for habitat recovery and economic reasons. To test the hypothesis that switchgrass (*Panicum virgatum* L.) hedges planted at 0.5-m vertical intervals within a gully would control erosion, we established a series of hedges in four concentrated flow channels. Two of the channels were previously eroded trapezoidal channels cut into compacted fill in an outdoor laboratory. The other two channels were natural gullies located at the margin of floodplain fields adjacent to an incised stream. While vegetation was dormant, we created artificial runoff events in the two laboratory gullies and one of the natural gullies using synthetic trapezoidal-shaped hydrographs with peak discharge rates of approximately 0.03, 0.07, and 0.16 $m^3 s^{-1}$. During these tests we monitored flow depth, velocity, turbidity, and soil pore water pressures. The fourth gully was subjected to a series of natural runoff events over a five-month period with peaks up to 0.09 $m^3 s^{-1}$. Flow depths in all tests

[1] Author to whom correspondence should be addressed.

were generally < 0.3 m, and flow velocities varied spatially and exceeded 2.0 m s^{-1} at the steepest points of the gullies. Erosion rates were negligible for controlled flow experiments, but natural flows in the fourth gully resulted in 1 m of thalweg degradation, destroying the central portions of the grass hedges, most likely due to the highly erodible nature of the soils at this site. Geotechnical modeling of soil steps reinforced with switchgrass roots showed that factors of safety > 1 for step heights < 0.5 m, but instability was indicated for step heights >1 m, consistent with our observations.

Keywords. Erosion, vegetative barriers, grass hedges, buffers, runoff, soil conservation.

INTRODUCTION

In tropical areas, planting vetiver grass (*Vetivaria zizainoides* L.) hedges has been used as a soil and water conservation practice for over 50 years (Vélez, 1952). However, it was not until 2001 that the United States Department of Agriculture - Natural Resources Conservation Service (NRCS) officially added the use of grass hedges to their National Handbook of Conservation Practices, with the title "Vegetative Barriers, Code 601." In this paper we will use the more descriptive term "grass hedge" interchangeably with the more general "vegetative barrier." The vegetative barrier practice is designed for controlling runoff and thereby reducing soil erosion by water in cropland and for stabilizing steep slopes. However, control of gullies in non-cropped areas is not included in this standard.

Where floodplains are farmed adjacent to deeply incised stream channels, streambank failure frequently occurs by mass failure, and gullies form where overbank runoff concentrates. In the United States, such edge-of-field gullies are normally controlled with "drop-pipe" structures comprised of earthen dams drained with a pipe culvert (Shields et al., 2002; Trest, 1997). Drop-pipes have proven quite effective, but require capital investment and eventually deteriorate due to corrosion (metal pipes) or by burning in wild fires (plastic pipes).

Throughout most of the United States where winter temperatures drop below -15°C, switchgrass (*Panicum virgatum* L.) forms more robust barriers than vetiver grass. Switchgrass is a tall, coarse species with the longest root system of all grasses comprising the native American prairie (Weaver, 1968). Some switchgrass accessions form aerenchymous roots that help the plants survive waterlogged conditions. Switchgrass roots also form rhizomes. These are very short in most strains so that the grass is generally characterized as a bunch grass, but when planted in a single row, most accessions can form a functional hedge.

Flume studies have shown that switchgrass hedges can remain erect in flows great enough to produce head losses exceeding 0.4 to 0.5 m across the barrier (Temple and Dabney, 2001). We concluded from these flume studies that intact single-row grass hedges could keep upstream flow velocities below critical limits for specific discharges less than 0.2 $m^2 s^{-1}$, and we hypothesized that grass hedges placed at 0.5-m vertical intervals would protect the gully bed by creating a series of low-velocity backwater areas (Dabney et al. 2002). If successful, gully control with grass hedges would be less capital-intensive than the structures described above and would replace the eroding gully with habitats associated with a stand of native grass. Grass barriers also offer a promising alternative to long-recognized methods of gully control such as rock and brush check dams (e.g., Heede, 1976). Grass hedges have the advantages of root systems and the ability to re-grow when partially buried by sediment.

The success of grass hedges for gully control, however, is uncertain during the period of plant establishment. For example, erosive flow velocities might develop just downslope of each grass hedge whenever backwater effects do not fully cover regions between hedges (Fig. 1). If the hedges are not destroyed or flanked by erosion, trapped sediment will raise the bed level upslope of each hedge, while erosion lowers it downslope, producing a series of "steps" stabilized by the grass. Slopes between hedges will be reduced so that hydraulic conditions will be non-erosive for all flows. During this "mature" phase, the grass roots will likely play an important role in preventing mass failure of the "steps" and in attenuating the scour effects of the reverse roller developed below the overfall.

The objectives of this study were to evaluate the effectiveness of a series of vegetative hedges in controlling gullies formed in a range of soil types. The test plantings were subjected to a range of surface and subsurface stresses associated with varying slopes, flows, soil moisture regimes, and vertical spacing of hedges.

MATERIALS AND METHODS

The grass hedge concept was tested in three experiments with increasing levels of environmental stress:

1. Established hedges growing in two nearly identical artificial gullies (S5 and S6) cut into compacted, cohesive fill were subjected to a series of controlled, nearly sediment-free flows.

2. Established hedges growing in a natural gully (L3) formed in highly erosive soils were subjected to a similar series of controlled, sediment-free flows.
3. Established hedges growing in fill placed in a natural gully (R4) were subjected to a season of natural runoff events from cultivated fields.

For Experiment 1, we established a series of six grass hedges in each of two outdoor test channels (sites S5 and S6) at the USDA – Agricultural Research Service (ARS) Hydraulic Engineering Research Laboratory at Stillwater, OK, USA (Fig. 2). These "gullies" were initially constructed as trapezoidal channels with 0.91-m-wide bases and 1H:1V side slopes cut into compacted fill borrowed from the 0.2 to 1.5 m depth of a nearby Pulaski fine sandy loam soil (Coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents). The channels were built with an average 3H:1V slope. Channels were lined with bermudagrass (*Conodon dactylon* (L) Pers.), and used for simulating erosion of embankment dams subjected to overtopping (Temple and Hanson, 1998). Each channel was tested in 1997 with a flow rate of 1.1 $m^3 s^{-1}$ for 64 to 75 hours, resulting in the formation of a gully with an approximately 1-m deep headcut near each toe (Fig. 2). These headcuts were left to weather in the eroded condition creating regions along the middle portion of the slope as steep as 2H:1V. Switchgrass hedges were transplanted in spring 2000, and protected from flow for two years while the switchgrass became established and shaded out remnant bermudagrass. Runoff was excluded from both Stillwater test gullies during switchgrass establishment, and supplemental irrigation was applied to ensure adequate grass growth. A pool of water was maintained in a depression near the crest of each channel to create a phreatic surface within the underlying soil.

Gullies tested during Experiments 2 (site L3, Fig. 3) and 3 (site R4, Fig. 4) were natural gullies draining from fields into a sinuous reach of Little Topashaw Creek (33.7457 N, -89.1750 W) in Chickasaw County, MS, USA. At the study location, the stream channel was incised about 6 m from its flood plain, had a top bank width of about 35 m, had a bed slope was about 0.002, and drained a watershed of about 37 km^2. Adjacent to the study reach, five fields comprising 75 ha were cropped to cotton (*Gossypium hirsutum* L.) and corn (*Zea Mays* L.). The dominant soil type was Arkabutla silt loam

(Fine-silty, mixed, active, acid, thermic Fluvaquentic Endoaquepts). Gullies were “shaped” to smooth contours with a track hoe prior to planting hedges of transplanted switchgrass, producing slopes of about 2.5H:1V or more gradual. Shaping of the gully for Experiment 3 (R4) included placing uncompacted fill. This gully was protected during the period of grass establishment by diverting all runoff away from the upstream end of the gully for two growing seasons.

Preliminary studies (Dabney et al. 2002 and 2004) were used to determine the hydrograph characteristics to be used in our controlled flow tests (Experiments 1 and 2). Controlled flows applied during Experiments 1 and 2 were trapezoidal-shaped “hydrographs” with peak discharges of 0.03, 0.07, and 0.16 $m^3 s^{-1}$ and durations ranging from 0.5 to 3 hours. Flows during Experiment 3 were entirely natural runoff. A total of 19 events were gaged over a period of 3 months, with peak flows ranging from 0.001 to 0.091 $m^3 s^{-1}$ and durations ranging from 0.3 to 4 hours.

During each of the simulated hydrographs in Experiments 1 and 2, we monitored depth and depth-averaged velocity at one-minute intervals at four locations using acoustic Doppler instruments (ADV), turbidity at two points using two optical backscatter instruments, and positive and negative soil water potentials at depths of 0.15, 0.3, 0.45, 1.0, and 1.5 m using tensiometers. Turbidity readings were calibrated to suspended sediment concentration as described by Dabney et al. (2004) and used in conjunction with total station thalweg surveys to compute the quantity of sediment eroded between the instruments. High water marks were flagged during each peak discharge to establish water surface profiles. Additionally, during Experiment 1, static manometers were placed upstream of each barrier. Following each test, we used a total station to survey high water marks and thalwegs. Depth and velocity were not monitored during the natural events of Experiment 3, but flow rates were measured using a 0.45-m metal H-flume, and precipitation records were obtained using a recording tipping-bucket gage. Flow rates were converted to unit discharges by assuming a flow depth and measuring a flow width from topographic surveys of the gully.

Soil particle size distributions and bulk densities were determined at each site using standard techniques. Soil cohesion and friction angle were determined from consolidated/drained triaxial tests and unconfined compression tests (US Navy, 1986) at Stillwater (Experiment 1) and bore-hole shear tests (Luttenegger and Hallberg, 1981) at Topashaw (Experiments 2 and 3). We determined soil conductivity by the shallow-well pump-in method (Amoozegar and Wilson, 1999).

Hedge vegetative characteristics were determined prior to testing by counting all stems within 0.5 m sections of each hedge; measuring the width of each hedge (in the direction of water flow) at both ends of this counted section at elevations of 0.05 and 0.3 m above the soil surface; determining the internode diameter of three representative stems at heights of 0.05, 0.3, 0.6, and 1.0 m in each hedge; and determining the largest gap in each hedge by inspection. During Experiment 1, a screen was set up in the drainage channel downstream from S5 in order to trap stems washed from the hedges.

In order to study the effect of switchgrass hedges on the stability of steps or headcuts within the gullies, we utilized the ARS Bank Stability Model v.3.4 (Simon et al., 2000; http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/bank.html, accessed September, 2003) that calculates a slope factor of safety (Fs) as the ratio of resisting strength to shearing force for a planar failure surface. Unfortunately, the model does not simulate the influence of seepage or sapping on slope stability, the importance of which likely varies with soil types. We separately and jointly compared the offsetting influences of increased cohesion due to root reinforcement and the destabilizing force of the extra weight of ponded water. Because we were interested in the stability of step heights less than 1 m high, we modified the model to permit the effect of switchgrass root reinforcement on apparent soil cohesion to be distributed through three shallow soil layers using data presented by Simon and Collison (2002): 30 kPa for 0 to 0.2 m, 10 kPa for 0.2 to 0.5 m, and 1.1 kPa for 0.5 to 1.0 m. We further modified the model to account for the additional horizontal hydrostatic force on the grass hedge and the vertical force on the soil failure block due to the weight of 20 cm of ponded water. We ran (1) a sensitivity analysis of Fs for a headcut in a silty soil as a function of step height, and (2) a stability analysis using the measured field conditions of our study sites.

RESULTS AND ANALYSES

SOIL CHARACTERISTICS

Characteristics of the soils at the study sites are summarized in Table 1. The biggest difference in soils was the greater bulk density (ρ_b) and lower saturated conductivity (K_{sat}) of the constructed embankment at Stillwater compared to the natural alluvial deposits at Topashaw. Since the Stillwater channels (Experiment 1, sites S5 and S6) were constructed in engineered fill, only a single (0 to 1.2 m) depth increment was sampled for soil properties. Topashaw soils (Experiments 2 and 3, sites L3 and R4) were siltier near the surface, and became much sandier with depth. Neither the Stillwater channels nor L3 had appreciable cohesion (c') when saturated, and both sites had a soil friction angles (ϕ') between 22 and 40 degrees. Based on the available data, R4 soils likely had values of cohesion and friction angle similar to L3 (Table 1).

VEGETATION CHARACTERISTICS

Properties of vegetation hedges prior to testing at each site are characterized in Table 2. Barriers were wider at Topashaw site L3, but denser in the other channels, where flow was excluded during plant establishment. The ability of the hedges to resist concentrated runoff is indicated by the MEI product (Kouwen, 1988) of stem density, modulus of elasticity, and moment of inertia of individual stems. Measured values at all sites except R4 were nearly equal to or less than the value of 50 N known to withstand unit discharges of 0.2 m^2 s^{-1} (Dunn and Dabney 1996). The lower MEI values were the result of lower stem densities due to competition between hedges planted close together on steep slopes, compact and/or infertile soil conditions, and washouts during the establishment period.

FLOW CHARACTERISTICS

Key characteristics of test flow events are summarized in Table 3. The highest total discharges for the controlled flow events (Experiments 1 and 2) exceeded total runoff gaged during the largest natural events (Experiment 3), but the sum of the discharges for all of the gaged natural events was 1570 m^3. Peak flow rates for controlled flows were quite similar, as planned, but unit discharges (flow discharge divided by flow width) varied by a factor of two among the largest events because the steeper Stillwater channels were narrower. Although the graded ("shaped") contours of both L3 and R4 produced flow widths on the order of 1.5 to 5 m at flow depths of 0.5 m (Fig. 1), progressive failure at R4 undercut the center of several hedges and created a (~0.3-0.4-m wide) "notch" down the thalweg of the gully, concentrating flows and eventually scouring the gully bed as much as 1 m (Fig. 5). Unit discharges of flows confined to the narrow channel reached 0.09 m^2 s^{-1} (Table 3), roughly twice as high as those observed in controlled flow testing, but still less than the maximum loading (0.2 m^2 s^{-1} , Temple and Dabney 2001) that could have been withstood by intact hedges.

The depth, velocity, and depth-velocity product (VD) presented for Experiments 1 and 2 are the range of time-averaged values recorded by four ADV loggers in each gully (Fig. 2 and Fig. 3) during the "peak" discharge. In a given flow event, the temporal variation in flow conditions recorded by a given ADV (CV = 11% for depth; CV = 29% for velocity; CV=31% for VD) was less extreme than variation between sampling points. This reflects the different conditions immediately above and below individual grass hedges. However, even the variation between the four ADV loggers (Table 3) does not fully reflect the total variation in flow depth recorded with surveys and static manometers (Fig. 5). Flow was characterized by a series of hydraulic jumps. Usually, jumps began upslope of a vegetative hedge but did not reach their sequent depths until they passed the hedge. Some flow passed through the hedges, but most passed over the top in the jump that cascaded down slope either as free-fall or adhering to bent over grass stems until plunging into the soil surface or a backwater pool created by the next downslope barrier. Water depth was least, and velocity and VD greatest, in the overfall nappe downslope of hedges on steep slope segments.

The range of measured VD (Table 3) exceeded the range of specific discharges previously tested in flumes (Temple and Dabney, 2001). The higher observed VD is evidence of flow concentration at the ADV locations (gully centerlines). Earlier tests featured hedges that were similar to those tested here

(Table 2) but were denser (approximately 300 stems m^{-1}) because they grew widely spaced in well-watered channels and thus were not subjected to competition or washouts (Temple and Dabney, 2001). Peak velocities during Experiment 1 (events 2 through 4 in S5 and S6, Table 3) exceeded the critical value for bare soil of 0.6 m s^{-1} by 200 to 400%. These locally high velocities were associated with bending and overtopping of the hedges, causing non-uniformity in flow conditions across the gully. High local velocity and VD values were associated with increased soil erosion inferred from turbidity data (Table 3).

Maximum measured velocities at specific points during Experiment 2 exceeded the critical value for bare soil by 10 to 45%, and maximum recommended slopes were locally exceeded at the upper end of the gully (Fig. 5). Since the soil was somewhat vegetated between switchgrass hedges at this site, it is not surprising that the observed erosion was small (Table 3), and did not increase with flow rate. In contrast, major erosion occurred during the natural events of Experiment 3, even though the associated peak flow rates were less, and hedge densities were greater than those in Experiments 1 and 2.

The total numbers of stems recovered from below S5 were 4, 22, 11, and 127 after events 1, 2, 3 and 4, respectively. Thus, overtopping bent over many segments of the hedges, and broke off but removed less than 10% of the stems originally present in the dormant hedges. Stem removal would presumably be smaller if the hedges are green and growing rather than in the dormant condition tested.

MASS FAILURE

The dominant erosion feature observed during Experiment 2 was the mass failure of soil blocks, one of which contained part of the most downslope vegetative hedge during the recession period of event 4 (Fig. 5). This block failure followed deepening and widening of the plunge pool below the overfall, which initially was between 1 and 2 m high. Pre- and post-test surveying indicated a volume of 53 m^3 was eroded during the tests. Most of the removal came from creek sediments previously deposited in and around to a large woody debris structure and from older creek bank materials. Much of the erosion was associated with widening of the gully downslope of the lowest hedge and is therefore not fully reflected in thalweg profile (Fig. 5). Based on the volume of erosion and estimates of sediment and bank bulk density (Table 2), the mass of soil lost through migration of the gully headcut was 65 to 75 Mg, roughly 200 times that lost due to erosion between the turbidity sensors (Table 3). No similar block failure occurred at Stillwater where step heights between barriers did not exceed 0.5 m.

Figure 6 schematically illustrates how we employed the bank stability model to conduct an analysis of the influence of vegetative hedges on the likelihood of mass failure as a function of step height. In each test, we assumed a 57.5 degree (recommended for the given soil friction angle and cohesion) shear plane emerged at a 0.2 m undercut of a vertical bank made up of uniform silty material (friction angle = 30 degrees; cohesion = 5 kPa; saturated unit weight = 18 kN m^{-3}). We calculated the factor of safety, Fs, for step heights of 0.25 to 2.0 m under three test cases: (1) saturated step with no grass roots, (2) saturated step with added cohesion due to switchgrass roots (Simon and Collison, 2002), c_r, in layers 2, 3, and 4 (Fig. 6), and (3) a 20 cm deep water surcharge (layer 1) on top of a bank reinforced with switchgrass roots. Water surcharge was modeled as a soil layer with a density 1000 kg m^{-3} and zero strength (Fig. 6).

Modeled results indicate that the saturated step would be unstable for heights exceeding 0.7 m, while a saturated step reinforced with switchgrass roots would be stable up to a height of 1.7 m. Even with the extra weight of ponded water, the vegetated step was predicted to be stable to a height of about 1.5 m. However, this level of stability would be achieved only if the roots intersect the shear plane in layers 2, 3, and 4 (Figure 6). As step height increases, the shear plane moves away from the step edge and from the root zone of a narrow strip of vegetation located at the edge. The shear plane from a 1.5 m step height would emerge 1.2 m from the bank edge and could bypass much of the root-reinforced area of a narrow grass hedge. For root reinforcement to have the modeled effect, the width of the vegetation would have to increase as step height increased. For step heights up to 0.5 m, used as a design value in the current study, the shear plane would be completely contained within the root-reinforced zone of even a narrow hedge. For this design step height, Fs = 3.6 even with a 20 cm water surcharge, so no mass failure would be expected. In fact, even when soil cohesion was set to zero other than that provided by switchgrass roots, the model predicts Fs > 1 for step heights up to 1 meter. A note of caution, this analysis does not apply to cracking soils where roots might be severed by desiccation cracks.

When we applied the bank stability model to the pre-test L3 thalweg profile (Fig. 5), without any undercutting or root reinforcement, using geotechnical data from Table 1 and assuming a saturated profile, the estimated Fs = 0.97. Thus, the initial profile approximates an equilibrium bank shape for the site without vegetation or water surcharge. At the time that mass failure was observed at L3, measured pore water pressures included a saturated surface horizon, an unsaturated zone with pore water pressure = -5 kPa between 0.5 and 1.0 m depth, another deeper saturated zone with artesian pressure of 4 kPa below 1.0 m. The scour hole had created a 30 cm undercut at the toe of the plunge pool where the shear plane emerged at a depth of 1.6 m below the hedge (about 89 m above MSL, Fig. 5). When we modeled these conditions, Fs = 0.78 without root reinforcement and Fs = 1.72 with root reinforcement. We believe that in this case, the shear plane partially bypassed much of the switchgrass root zone so that root reinforcement was incomplete, resulting in mass failure. In addition, the model (Simon and Collison 2002) may overestimate the contribution of roots to soil strength because it assumes that all roots break simultaneously as soil shears. When applied to the gullies tested in Experiments 1 and 3, Fs was above 10 for the duration of the tests.

ROOT REINFORCEMENT

After Experiment 1, inspection showed that there had been some local scour of soil between hedges 3 and 4 (counted from the top, Fig. 2) in S5 and between 4 and 5 in S6. Both locations were on lower portions of the steepest regions of the gully (~ 2:1, or 27 degrees, Fig. 2). In S5, we counted 3700 roots/m^2 protruding from exposed surfaces located about 30 cm below the plant crown, and the mean root diameter was 0.38 mm, median diameter was 0.1 mm, and root area ratio (ratio of the total root cross sectional area to planer soil surface sampled) was 0.0015. In S6, we counted 2900 roots/m^2 protruding, the mean root diameter was 0.69 mm, median diameter was 0.4 mm, and root area ratio was 0.0022. This curtain of exposed roots undoubtedly disrupted the impinging wall jet (Alonso et al., 2002) and reduced local scour during the period of our tests but may not have provided sufficient protection during prolonged flows. This local scour could have been more severe for a less compact, more erodible soil.

After Experiment 2 was completed, we counted roots protruding from the 60 cm deep failed block at the lower end of L3. Root density (2200 roots/m^2) was lower than for S5 and S6, but root size and root area ratio were larger. The mean root diameter was 1.0 mm, median diameter was 0.6 mm, and root area ratio was 0.0028, similar to that reported for switchgrass at 20 cm depth by Simon and Collison (2002). This suggests that our application of their data for c_r in the mass failure analysis was appropriate. However, prior to the L3 block failure, and in addition to the deepening and widening of the plunge pool at the base of the overfall (Alonso et al., 2002), we observed progressive oozing and sloughing of soil away from roots as a result of seepage flow (Crosta and di Prisco, 1999) and adhesive flow (Oliveria, 2001). Thus, prior to shearing failure, some of the roots on the overfall side and below the root ball of the vegetative hedge were hanging in the air as a curtain.

DISCUSSION AND CONCLUSIONS

The reasons that grass hedges were successful in stabilizing gullies in Experiments 1 and 2 but not Experiment 3 are not entirely clear, although a comparison of some of the key conditions for each experiment is revealing (Table 4). In all three experiments, the hedges had been in place for two growing seasons. Since root depth and development increase the durability of hedges to resist undercutting and mass failure, hedge reliability should increase with age over the first few years, depending on site conditions. In some ways, Experiments 1 and 2 were more rigorous tests of the grass hedges, since flows were clear and hedges were dormant throughout the period of testing. However, soils underlying the Experiment 3 gully (R4) were more erodible, and when subjected to a sequence of natural events, this site responded by a deep, narrow central notch that served as positive feedback to erosion processes. Experiment 1 erosion rates might have been considerably higher if the Stillwater soil had not been compacted to a bulk density of 1.78 Mg m^{-3}, since erodibility of this material can decrease by two orders of magnitude if bulk density is increased from 1.70 and 1.85 Mg m^{-3} (Hanson and Temple, 2002).

Concentrated flow soil erosion rates increase dramatically when knickpoints form and migrate headward. A series of grass hedges encourages the development of steps and knickpoints in the bed of a gully (Fig. 1). On the other hand, the tall, thick grass stems greatly increase the roughness of the channel, slowing flow, and the dense root systems add to the cohesion of the soil. The question becomes, can the vegetative hedges that encourage the development of steps prevent knickpoint migration?

Conceptually, flow control by grass hedges can be divided into three regimes. During <u>low flow</u>, backwater depth insufficient to protect the entire upstream reach between hedges and erosion below the hedge, deposition above the hedge is the dominant process (Fig. 1, top). Through an <u>intermediate flow</u> range, the hedges remain upright, tailwater protects the areas immediately downstream of the hedges, and the erosion/deposition processes are substantially damped (Fig. 1, bottom). For <u>higher flows</u>, the hedges are locally overtopped, flow is concentrated, and the protective capability of the hedges results from a combination of the "prone" stems reducing velocity near the bed, the ponding effect reducing mean velocity, and the energy loss associated with the resulting high turbulence in some areas, where boundary adjustment rates depend on soil erodibility.

Observations at Stillwater (Experiment 1) suggest that gully slopes treated with grass hedges must be $\leq$ 3H:1V even when vertical intervals are < 0.5 m because of: (1) retardation of hedge development due to plant crowding and (2) the dimensions of hydraulic jumps. Switchgrass is a plant that thrives in full sunlight. When planted at a vertical spacing of 0.5 m, horizontal spacing would be only 1.0 m apart on a 2H:1V slope. This crowding would cause competition that would limit hedge growth and development (hedge width, stem density, stem diameter). The situation would be aggravated in northern-facing or deeply incised gullies. A second constraint on gully slope is provided by hydraulic jump behavior. Increasing bed slope generally increases the Froude number, increases the height and length of a hydraulic jump, and moves the jump initiation point downslope. When the sequent depth of the jump exceeds the flow depth at a hedge, the maximum flow depth is not reached until the flow is past the hedge, and the jump takes the form of a "standing swell," which well describes Experiment 1 observations. On the steepest portions (~2H:1V) of S5 and S6, the overfall nappe leaving the swell bypassed the next hedge and plunged into the backwater created by the second downslope hedge (Fig. 5). This greater fall allowed acceleration of the overfall nappe (Alonso et al., 2002) and enhanced the local scour that exposed roots. Empirical relationships for hydraulic jump dimensions (Chow 1959) support the conclusion that a 0.5-m hedge spacing on a 3H:1V slope would allow each hedge to create its own jump without being bypassed.

The results of this study indicate that stabilizing gullies with a series of grass hedges has potential, but more research is needed to improve reliability. Established switchgrass hedges with a 0.5-m vertical interval on slopes $\leq$ 3H:1V were effective in preventing measurable erosion during 8 hr of testing with specific discharges up to 0.09 $m^2\ s^{-1}$. Energy was effectively dissipated in a series of cascading hydraulic jumps. Erosion by mass failure was not observed when step heights between hedges $\leq$ 0.5 m. However, mass failure was the dominant mechanism where conditions at the gully mouth produced a hedge with a 1- to 2-m overfall. Specific discharges of about 0.09 $m^2\ s^{-1}$ did produce significant thalweg erosion and undercutting of grass hedges in a gully formed in sandy soils with low (~1.3 Mg m^{-3}) bulk densities. Protection of such highly erodible soils exposed between hedges using turf reinforcement mattresses or similar products might render this type of gully treatment more robust.

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TABLES

Table 1. Soil characteristics of the tested gullies

Experiment	Location (site), Sample depth m	Organic Matter %	Sand %	Silt %	Clay %	ρ_b Mg m^{-3}	K_{sat} mm h^{-1}	ϕ' degrees	c' kPa
1	Stillwater (S5 and S6)								
	0 to 1.2	0.27	57	30	13	1.78	4.8	40	0
2	Topashaw (L3)								
	0 to 0.15	1.80	34	55	11	1.28			
	0.15 to 0.3	0.53	66	25	8	1.42	34.8		
	0.3 to 0.6	0.35	76	18	6	1.53	34.9	28	3.3
	0.6 to 0.9	0.50	60	31	9			24	2.3
	0.9 to 1.5	0.35	73	20	7			22	1.3
3	Topashaw (R4)								
	0 to 0.5	1.63	9	71	20	1.34			
	0.5 to 1	1.29	18	65	17	1.41			
	1 to 1.6	1.32	11	70	19	1.40			
	1.6 to 2.1	0.54	40	47	13	1.53			
	2.1 to 2.6	0.26	56	34	11	1.63			

Table 2. Average characteristics of switchgrass hedges in each gully prior to testing.

Experiment	Location (site)	Width[2] Hedge @ 0.05 m height m	Width Hedge @ 0.30 m height m	Stems per meter of Hedge m^{-1}	Stem Internode Diameter mm	Average Maximum Gap in Hedge m	MEI[3] @ 0.15 m N
1	Stillwater (S5)	0.25	0.54	178	5.1	0.12	51
1	Stillwater (S6)	0.23	0.52	199	4.4	0.08	32
2	Topashaw (L3)	0.45	0.65	107	4.6	0.18	25
3	Topashaw (R4)	0.33	0.80	331	5.0	0.11	71

[2] The word "width" when applied to a grass hedge refers to the dimension parallel and not perpendicular to flow.

[3] product of stems per m^2, modulus of elasticity assumed to be 3.5 GPa, and moment of inertia calculated from average stem diameter (Dunn and Dabney, 1996).

Table 3. Total discharge during each run, flow characteristics during the quasi-steady peak of each run, and total erosion or deposition between the two turbidity sensors.

Location/Event	Total Discharge m^3	Peak Flow Characteristics					Erosion (+) or Deposition[4] kg
		Flow $m^3 s^{-1}$	Unit Discharge $m^2 s^{-1}$	Velocity $m s^{-1}$	Depth m	VD $m^2 s^{-1}$	
Experiment 1 (Stillwater S5)							
1	48	0.035	0.02	0.14 to 0.18	0.08 to 0.22	0.03 to 0.04	16
2	198	0.079	0.02	0.16 to 2.46	0.10 to 0.29	0.04 to 0.37	40
3	296	0.067	0.04	0.09 to 1.67	0.07 to 0.21	0.02 to 0.24	42
4	1085	0.166	0.09	0.71 to 2.08	0.09 to 0.22	0.16 to 0.36	272
Experiment 1 (Stillwater S6)							
1	32	0.020	0.01	0.06	0.12 to 0.14	0.01	45
2	201	0.082	0.04	0.03 to 1.51	0.10 to 0.25	0.01 to 0.17	87
3	308	0.069	0.04	0.15 to 1.36	0.09 to 0.19	0.03 to 0.13	200
4	1116	0.169	0.09	0.08 to 1.71	0.09 to 0.20	0.01 to 0.21	296
Experiment 2 (Topashaw L3)							
1	84	0.043	0.02	0.15 to 0.66	0.12 to 0.18	0.02 to 0.06	-112
2	203	0.069	0.04	0.39 to 0.87	0.09 to 0.23	0.06 to 0.09	160
3	353	0.064	0.03	0.35 to 0.85	0.10 to 0.22	0.06 to 0.11	133
4	676	0.138	0.05	0.46 to 0.66	0.14 to 0.27	0.09 to 0.18	57
Experiment 3 (Topashaw R4)[5]							
1	53	0.007	0.01				
2	94	0.020	0.02				
3	209	0.079	0.08				6,000
4	224	0.055	0.06				
5	234	0.091	0.09				
6	562	0.091	0.09				

[4] Between turbidity sensors in tests 1 and 2. Erosion at L3 excludes about 70,000 kg eroded by mass failure of soil blocks at large headcut at gully mouth (Fig. 5).

[5] Only the events with the six largest peaks are shown, sorted in ascending magnitude. Erosion was observed over an entire high flow season, which involved at least 19 events.

Table 4. Summary of experiments.

Experiment	Location (site)	Mean (Max) gully slope	Hedge establishment	Hedge width m	Average maximum gap in hedge m	Soil conditions	Mean bulk density of soils Mg m^{-3}	Total discharge m^{-3}	Total discharge duration hr	Peak unit discharge $m^2 s^{-1}$	Outcome
1	Stillwater (S5 & S6)	3H:1V (2H:1V)	Protected for two growing seasons	0.54	0.12	Compacted fill	1.78	1640, clear water from reservoir	8	0.09	Negligible erosion
2	Topashaw (L3)	5H:1V (2.4H:1V)	Natural (but small) flows during two growing seasons	0.65	0.18	Natural gully, graded to smooth shape	1.3-1.5	1320, clear water from stream	7	0.05	Negligible erosion in protected region of gully, but major mass failure at downstream headcut
3	Topashaw (R4)	2.6H:1V	Protected for two growing seasons	0.80	0.11	Uncompacted fill to shape natural gully	1.3-1.5	1570, sediment-laden runoff from fields[6]	29	0.09	~ 1 m of thalweg degradation

[6] Flow-weighted composite runoff samples from 10 storm events at this site and an adjacent gully had suspended sediment concentrations ranging from 159-8,963 mg/L, mean = 2,430 ± 2,612 mg/L.

FIGURE CAPTIONS

Figure 1. Schematic of concept for stabilizing gully with a series of grass hedges placed at vertical intervals of 0.5 m

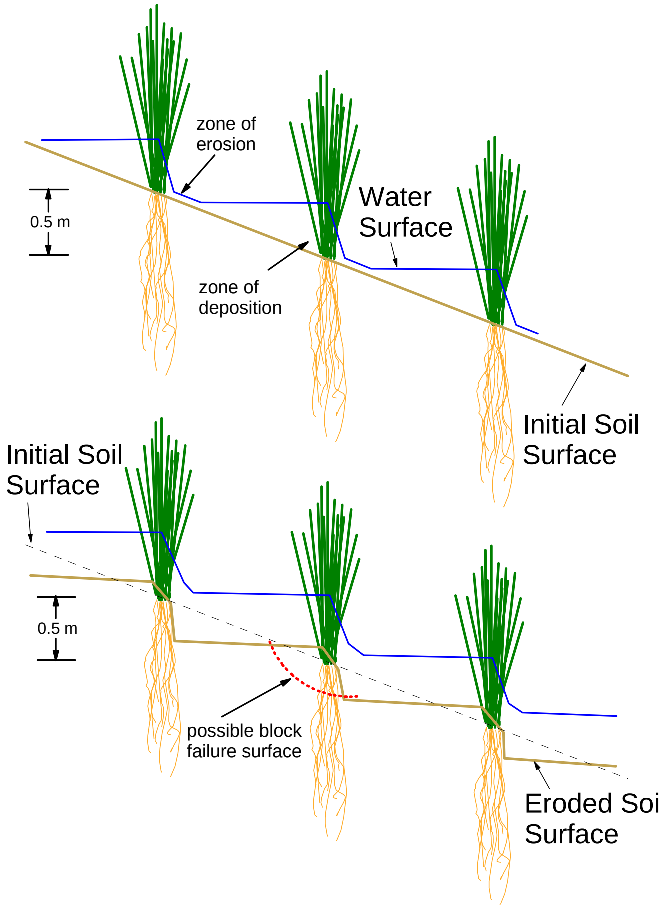
Figure 2. Shaded relief contour map (0.2 m contour interval) of pre-test conditions of test gullies for Experiment 1, showing the extent of grass hedges, locations of turbidity sensors (OBS), acoustic Doppler depth and velocity transducers (ADV), tensiometer nests (Tens), and pre-existing headcuts at the toe of each gully.

Figure 3. Shaded relief contour map (0.5-m contour interval) of pre-test conditions for Experiment 2 indicating locations of grass hedges, turbidity sensors (OBS), acoustic Doppler depth and velocity transducers (ADV), and tensiometer nests. Flow was introduced only into the northern arm of the gully. The location of a large woody debris structure that trapped creek sediments at the toe (LWD) is also indicated.

Figure 4. Shaded relief contour map (0.5 m contour interval) of pre-test condition of test gully for Experiment 3, showing the extent of grass hedges and location of H-flume.

Figure 5. Gully thalweg, high water profiles, and grass hedge locations during the first and last event at each location. Thalweg changes during Experiment 1 were not measurable. High water profiles for Experiment 3 were not measured.

Figure 6. Use of bank-stability model to determine the effect of switchgrass hedges on the likelihood of mass failure of steps in a silty soil as a function of step height.



zone of
erosion
0.5 m
Water
Surface
zone of
deposition
Initial Soil
Surface
Initial Soil
Surface
0.5 m
possible block
failure surface
Eroded Soil
Surface

FIGURE 1

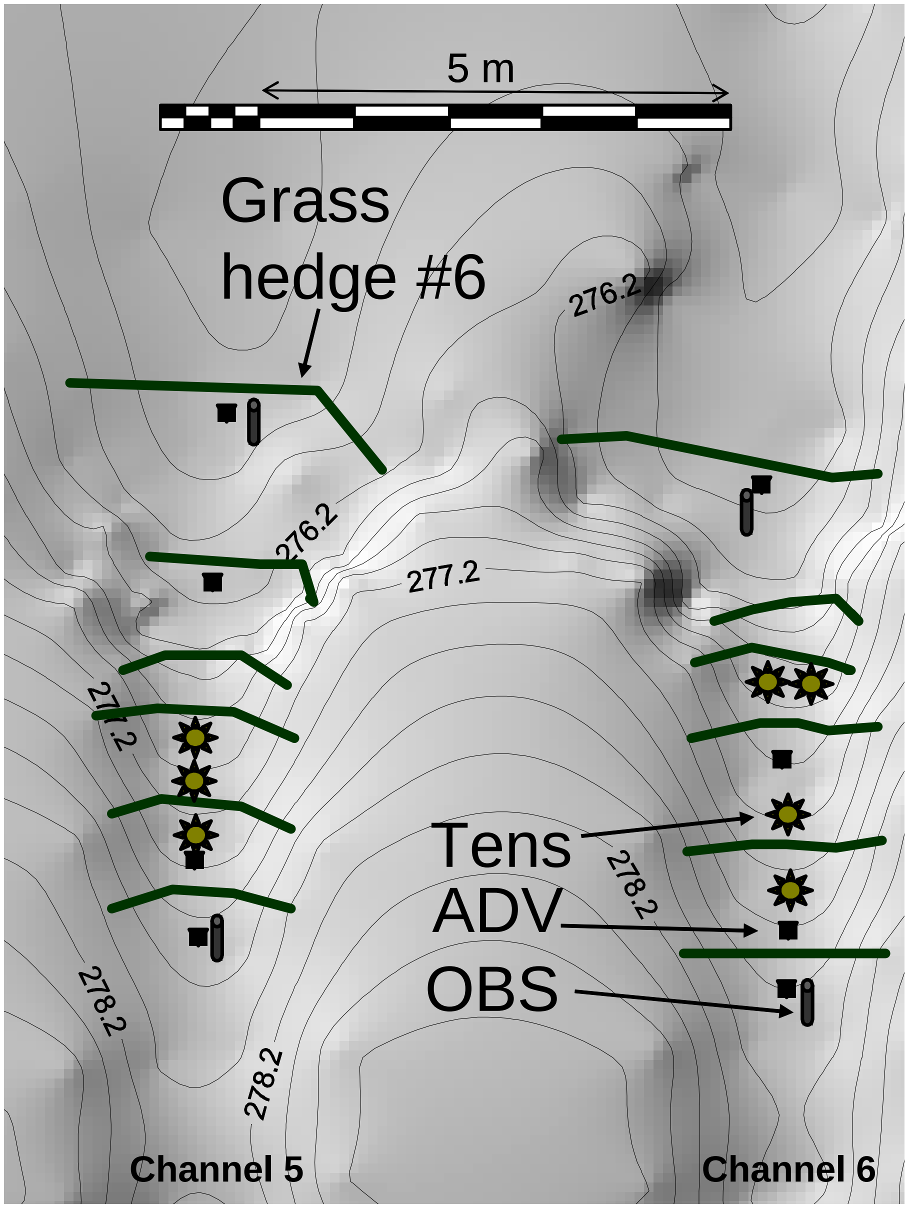

5 m
Grass hedge #6
276.2
276.2
277.2
278.2
278.2
278.2
Tens
ADV
OBS
Channel 5
Channel 6

Figure 2.

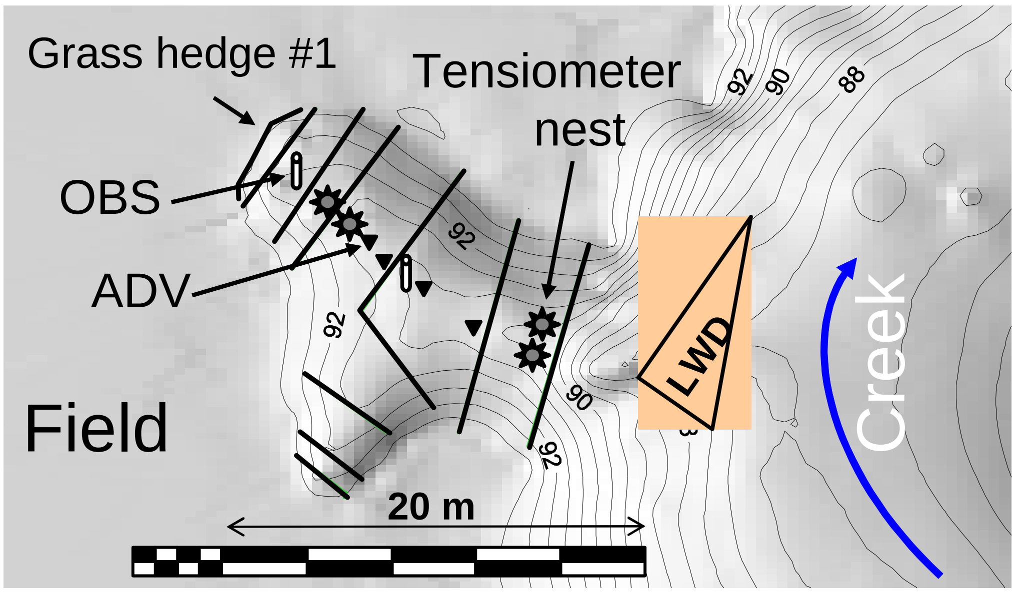

Grass hedge #1
Tensiometer nest
OBS
ADV
Field
LWD
Creek
20 m
92
90
88

Figure 3.

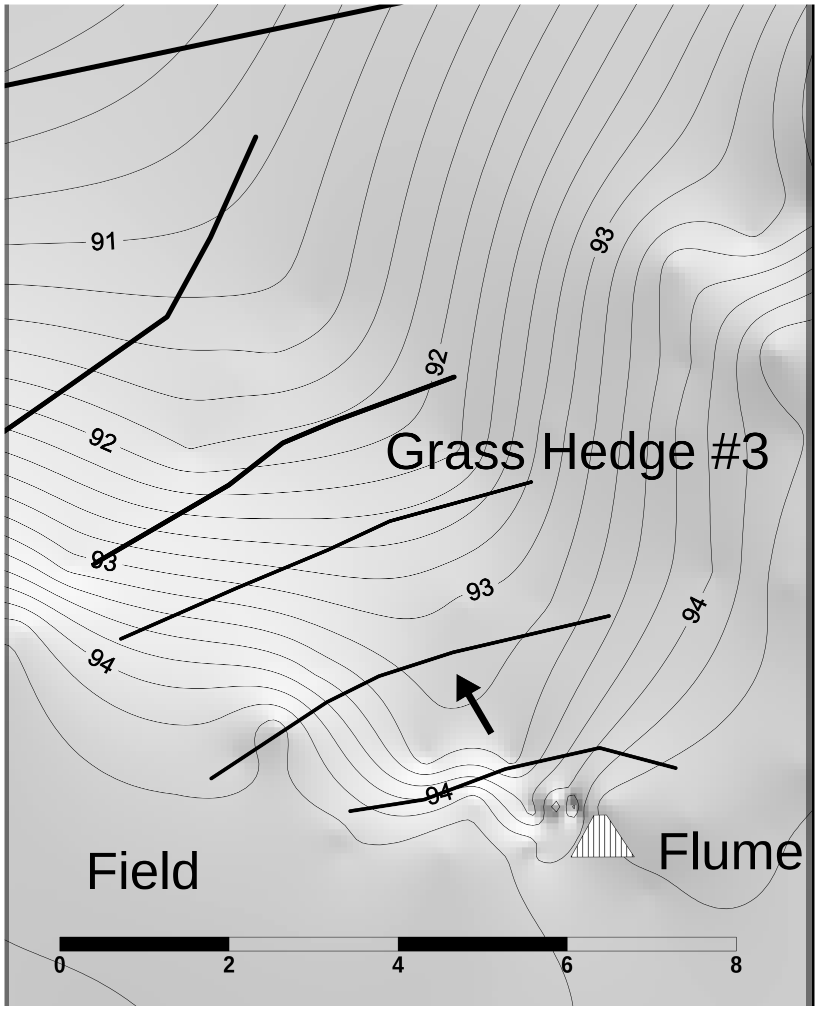


Figure 4.

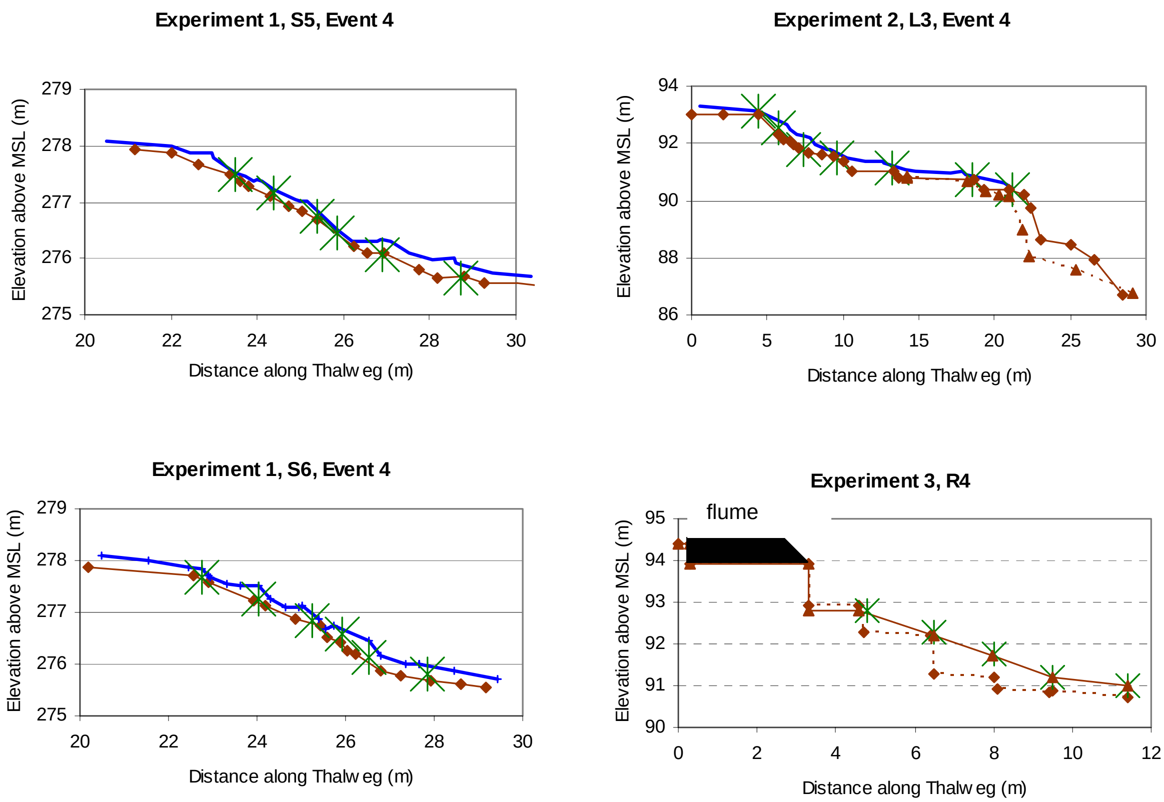

Experiment 1, S5, Event 4
Elevation above MSL (m)
279
278
277
276
275
20
22
24
26
28
30
Distance along Thalw eg (m)
Experiment 2, L3, Event 4
Elevation above MSL (m)
94
92
90
88
86
0
5
10
15
20
25
30
Distance along Thalw eg (m)
Experiment 1, S6, Event 4
Elevation above MSL (m)
279
278
277
276
275
20
22
24
26
28
30
Distance along Thalw eg (m)
Experiment 3, R4
flume
Elevation above MSL (m)
95
94
93
92
91
90
0
2
4
6
8
10
12
Distance along Thalw eg (m)

Figure 5

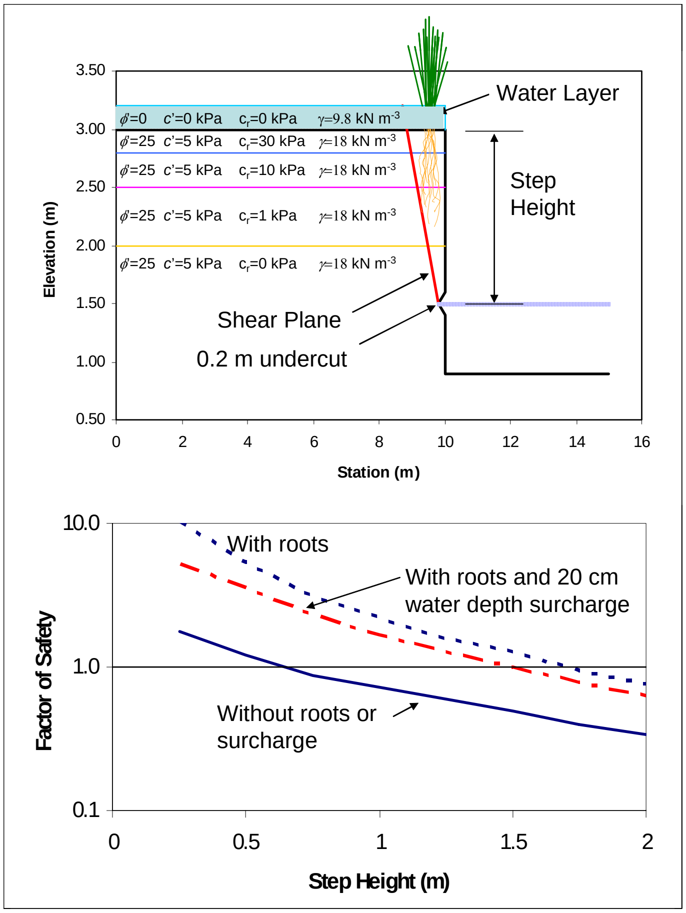

Water Layer
Step Height
Shear Plane
0.2 m undercut
Elevation (m)
Station (m)
With roots
With roots and 20 cm water depth surcharge
Without roots or surcharge
Factor of Safety
Step Height (m)

Figure 6.